

BD+30°3639: The infrared spectrum during post-AGB stellar evolution

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Abstract

We present a radiative-transfer calculation which reproduces the infrared spectrum of the planetary nebula BD +30°3639. We calculate the transfer process through absorption and scattering in a spherical-symmetric multi-grain dust shell. The emission of transiently heated particles is taken into account, as well as polycyclic aromatic hydrocarbons. We obtain an acceptable fit to most of the spectrum, including the PAH infrared bands. At submillimetre wavelengths the observed emission is larger than the model predicts, indicating that large dust conglomerates (“fluffy grains”) may be needed as an additional constituent. The fit favours a distance of ≥ 2 kpc, which implies that BD +30°3639 has evolved from a massive progenitor of several solar masses. A low dust-to-gas mass ratio is found in the ionised region. The calculations yield an original mass-loss rate of $2 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ on the Asymptotic Giant Branch. Using this mass-loss rate, we calculate how the infrared spectrum has evolved during the post-AGB evolution. We show in particular the evolution of the IRAS colours during the post-AGB evolution.

Key words: radiative transfer – dust, extinction – planetary nebulae: general – planetary nebulae: individual: BD +30°3639

1 Introduction

Low-mass stars in their latest stages of evolution play an important role for their host galaxies (e.g. bolometric luminosity, chemical evolution). By now it seems to be established that all stars with a main-sequence mass of $0.8\text{--}8 M_{\odot}$ form white dwarfs, evolving via the giant and asymptotic giant branch (AGB) through the planetary nebulae (PN) phase (Iben & Renzini 1983). On the AGB the stars undergo a large loss of mass and a large amount of dust is created, enriching the interstellar medium. While there exists a substantial amount of theoretical models describing the thermo-nuclear evolution of the cores of such stars (Weidemann & Schönberner 1989), the physical mechanism of mass loss from these stars remains unclear. Present understanding is to a great extent based on theoretical conjectures whereas observational data are scarce.

After the mass loss ends, the star rapidly becomes hotter, and quickly begins to ionize the expanding envelope. At present, the study of objects in the earliest phase of ionization (being in transition to planetary nebula) gives the best tool to study the preceding mass loss. In this paper, we therefore present a detailed study of a young planetary nebula, BD +30°3639. The infrared spectrum of this source has recently been modeled by Hoare et al. (1992, hereafter HRC). We use a dust model with additional components as compared to these authors; on the other hand, HRC also model the photo-ionisation which we do not include. After the dust parameters are derived, we develop a simple evolutionary scenario to describe how its infrared spectrum may have evolved. We have to solve two basic problems: i) The objects are highly embedded in an optically thick dusty envelope and the equation of radiative transfer has to be properly handled. ii) A more or less realistic description of the nature of circumstellar dust particles is required as well (Barlow 1993).

This article is structured as follows. In Section 2 we briefly describe a radiative-transfer model, which takes transiently heated particles and large molecules as the proposed carrier of the broad near- and mid-infrared emission features into account. We then fit the spectral energy distribution of the well-observed carbon-rich planetary nebula (PN) BD +30°3639 (Section 3). The fit parameters are discussed in Section 4. The calculated spectra at several stages of the preceding post-AGB evolution are presented in Section 5. We conclude with a summary of our findings in Section 6.

2 The dust–radiative-transfer model

2.1 The dust model

The dust model used in the present calculations is that of Siebenmorgen & Krügel (1992, henceforth SK). This model successfully reproduces observations ranging from near-infrared to millimeter wavelengths, including narrow-band data. The grain properties have been established by fitting extinction curves towards different lines of sight (e.g. Fitzpatrick & Massa 1988, Cardelli et al. 1989, Mathis 1990). The dust model is governed by a grain size distribution ($n(a) \propto a^{-q}$) with radii between approximately 2500Å down to molecular sizes of about 5Å (~ 25 atoms) in which we distinguish three different populations of dust particles:

- i) Large particles with sizes $a \geq 100\text{Å}$, $q = 3.5$, causing the far-infrared/submillimeter emission. We call these particles large because they have sufficient heat capacity that we can neglect the quantum-statistical behavior of photon-grain interactions. Since in this paper we only discuss carbon-rich environments which do not exhibit the Si-O stretching and bending modes at $9.7\mu\text{m}$ and $18\mu\text{m}$, silicate grains are not included. We have used two different sets of optical constants: (1) constants given by Draine & Lee (1984, 1987) for grains with graphite structure; (2) constants for amorphous carbon for $300\text{Å} \leq \lambda \leq 0.105\mu\text{m}$ published by Rouleau & Martin (1991) and for $0.105 < \lambda \leq 800\mu\text{m}$ by Preibisch et al. (1993). Compilation (2) is based on optical constants from Bussoletti et al. (1987) and Blanco et al. (1991) and re-analyzed by taking shape and clustering effects into account.
- ii) Small graphite grains with sizes $10\text{Å} \leq a < 100\text{Å}$, $q = 4$, emitting predominately in the mid-infrared. These particles show temperature fluctuations after individual energy-absorption events (e.g. with photons, electrons); to calculate their emission spectrum one has to consider multi-photon events. We use properties such as abundance, bulk density, absorption efficiencies and enthalpy of these small graphites as given in SK. Small graphites are at present the most popular candidates to explain the 2200Å extinction bump (Draine 1988, 1989; Sorrel 1989).
- iii) Small PAHs (~ 25 atoms) and larger PAH clusters (~ 250 atoms). Léger & Puget (1984) and Allamandola et al. (1985) have argued that these large isolated molecules explain the near- and mid-infrared emission bands. A review of the whole family of emission features between 3–14 μm can be found in, e.g., Allamandola et al. (1989a), Puget & Léger (1989) and Tokunaga et al. (1991). From the ratios of different emission bands a temperature of the emitting species can be derived; if one adopts a model for the heat capacity, a size can be estimated as well. By doing this for the 3.3/3.4 and 3.3/11.3 band ratios, de Muizon et al. (1990) found indications that PAHs also show a size distribution. The band ratios of the C–H to the C=C vibrational modes will be affected by the number of H atoms attached to the peripheral rings in a PAH. Therefore the hydrogen-to-carbon atom ratio is introduced, called the hydrogenation parameter. Emission coefficients of model PAHs are given by Léger et al. (1989a), d’Hendecourt et al. (1989) and more recently by de Muizon et al. (1990). PAHs absorb predominately in the far-UV and, as demonstrated in laboratory studies (Léger et al. 1989b, Joblin et al. 1992), an ensemble of these molecules can be responsible for the non-linear rise towards the UV in the extinction curve. Absorption efficiencies are calculated as described in SK for $\lambda \geq 912\text{Å}$. For shorter wavelengths we simply scaled the absorptivity to a small graphite particle of similar size (calculated with Mie Theory). In addition we have compared our method (for $\lambda \geq 912\text{Å}$) with the analytical fit given by Desert et al. (1990) and found a very good agreement.

2.2 The radiative transfer model

The solution of the radiative transfer problem for spherically symmetric dusty objects containing quantum-heated particles and including scattering by grains is described by Siebenmorgen et al. (1992). The method outlined for the photo-destruction of transiently heated particles is given by Siebenmorgen (1993). The procedure does not take into account the heating of the dust by the emission of ionized gas, nor does it treat any of the cooling lines observed between UV and far-IR wavelengths.

Important is the neglect of Ly α radiation: The HII gas emits Ly α photons and Lyman-continuum photons from recombination to the ground state, both of which are trapped in the HII region. Under certain conditions, Ly α radiation can dominate the heating of the grains and even cause their destruction. This happens especially if the HII region is heavily dust depleted, because the energy input from Ly α per grain is proportional to the number of Lyman continuum photons of the star that lead to ionization divided by the mass of the dust in the HII region. Since this is not presently included in the model, it is important to estimate the effects of this radiation, to understand the limitations of the present calculations.

In order to estimate the effect of especially the Ly α radiation, we attempted to calculate the structure of the ionized gas using the on-the-spot approximation. However, the location of the ionization front could not be fixed sufficiently accurately: this resulted in violation of the overall energy equation. Ignoring this problem, the results of this calculation did not indicate significant differences with those obtained without ionization and we did not find a qualitative change of the contribution of small graphites, PAHs or large-grain component to the overall spectral energy distribution. However, we cannot rule out that the Ly α radiation leads to significant PAH destruction. This can be important for a detailed discussion of the spatial distribution of the PAH band emission (see Section 4.3).

3 The infrared spectrum of BD +30°3639

3.1 Basic parameters

The program that has been developed to handle the theoretical framework outlined in the previous section allows flexibility in the specification of the various grain populations, the heating source, the dust density distribution, and other physical parameters. We adopt the dust model as discussed above. The heating source is described as a blackbody with an adopted stellar temperature T_* and bolometric luminosity. The density distribution can be arbitrary but is defined here by means of power laws $n(r) \propto r^\beta$.

3.2 Available data

BD +30°3639 is one of the best observed planetary nebulae in the infrared. All the PAH features are well observed (e.g. Allamandola et al. 1989b), including the 6.2 and 7.7 μ m bands which are not observable from the ground. New observations were communicated to us prior to publication (Schutte and Tielens 1993). Mid-infrared photometry obtained at the Kuiper Airborne Observatory (Moseley and Silverberg 1985), show that there is no 30 μ m emission bump, as seen in the other carbon-rich planetary nebulae NGC 7027 and IC 418. This feature is usually attributed to MgS grains or mantles (Goebel & Moseley 1985). Since our model does not include this feature, BD+30°3639 gives the best test case. Submillimetre observations have recently been published by HRC. These data points are crucial to constrain the density distribution at large distance from the central star. At wavelengths $\geq 800\mu$ m the emission is mostly due to the radio free-free emission: the 6 cm radio flux of 620 mJy (Basart and Daub 1987, Masson 1989) extrapolated to 800 μ m predicts a flux density of 400 mJy, which accounts for most of the observed value of 550 ± 34 mJy. At shorter wavelengths the emission is mostly due to dust. Finally, the nebula has been imaged at several mid-infrared bands (Hora et al. 1993, 1990). The model calculates the radial flux distribution, which can be compared with these observations.

3.3 Distance and luminosity

Two important input parameters of the model are the distance to the nebula and the luminosity of the central star. In our model, the total luminosity can be determined as one of the fit parameters, after a value for the distance has been chosen.

The distance to BD +30°3639 is controversial. HI absorption features indicate a distance of $\gtrsim 2.5$ kpc, but the low extinction ($E_{B-V}=0.24$, both from the ratio of the $H\beta$ flux over the radio flux density and from the depth of the 2200Å feature towards the star, Pottasch 1984) indicates a distance of about 0.6 kpc (Gathier et al. 1986). Masson (1989) has measured the expansion of the nebula from radio images, from which he derives a large distance of $2.8^{+48}_{-1.2}$ kpc. Hajian et al. (1993), using the same method, find a distance of 2.68 ± 0.81 kpc, in agreement with Masson. We have tried to fit the infrared spectrum using several different distances. For distances ≤ 2 kpc, the model required an inner radius of the circumstellar shell significantly smaller than the observed value (which is 1.5''–2'': Taylor et al. 1987, Masson 1989, Hora et al. 1990, 1993). This could be solved if we assume that the abundance of the very small grains is much higher than in the interstellar medium, although in the fit this parameter appears to be well constrained. At larger distances, the observed inner radius can be fitted by fine-tuning of the stellar luminosity without requiring changing the dust composition.

We adopt a distance of 2 kpc, the same distance as taken by HRC. This is close to the lowest value allowed by the radio expansion measurements of Hajian et al., and allows us to fit the spectrum without changing the abundance of the very small grains with respect to the interstellar medium.

An approximate luminosity can be obtained from the optically thin radio luminosity. The number of ionizing photons required to produce the observed radio flux can easily be calculated (e.g. Zijlstra and Pottasch, 1989), and for a given temperature of the central star converted to a total luminosity e.g. using a black-body atmosphere. Because direct absorption of ionizing photons by dust is ignored in this method, only a lower limit to the stellar luminosity is obtained. Using the known temperature of the central star of BD+30°3639 of 30 000 K (Pottasch 1984), we find a lower limit to the luminosity of $7 \times 10^3 L_{\odot}$ at a distance of 2 kpc, adopting a black-body atmosphere. More realistic atmosphere models would predict a somewhat higher luminosity. In the present model, we find that the best fit required a luminosity of $1.3 \times 10^4 L_{\odot}$; this is consistent with the limits derived above.

In principle the luminosity is determined by the temperature and optical magnitude of the star. However, the temperature of planetary-nebulae central stars is not generally known to sufficient accuracy for this to give useful results, especially because of the T^4 dependency. Also, the central star of BD +30°3639 is of [WC] type for which a black body is probably not a good approximation. The luminosity derived here is therefore probably the best available. As shown later, the K-magnitude of the star is reasonably well reproduced by the model.

3.4 The density distribution and dust composition

We find that a single constant-density component ($\beta = 0$) cannot reproduce the infrared spectrum. By using a constant density for the inner region, and a r^{-2} component in the outer region, a satisfactory fit is obtained. The use of a r^{-2} component is known to give a good approximation to the global density profile of planetary nebulae (e.g. Taylor et al. 1987); such a structure can be formed through a phase of constant mass loss. At smaller scales deviations can be expected from such a distribution: many planetary nebulae are known to show bipolar structures, which are evidence for asymmetric mass loss, and are affected in the inner parts by shocks and pressure inequilibrium arising from the ionization of the nebula. BD +30°3639 also shows enhanced density around the equatorial plane (which lies north-south, e.g. Basart and Daub 1987). However, the density contrast between pole and equator appears to be much less than seen in many other PN. Due to the combined effects of dust destruction and dust removal by radiation pressure, the dust density distribution may not perfectly follow that of the gas. The density distribution is a simplification, but it probably gives a reasonable approximation to the actual global structure.

The density structure is parameterized as:

$$\rho = \begin{cases} A_1 & \text{for } R_i < r < R_2 \\ A_2 r^{-2} & \text{for } R_2 < r < R_o \end{cases}$$

where ρ is the hydrogen density. The parameters are: the inner and outer radii R_i and R_o , the radius R_2 where the density changes from uniform to wind-like, and the two density constants A_1 and A_2 . The value chosen for the inner radius affects the slope of the near-infrared spectrum, because this emission is partly due to the hottest large grains which are found near the inner boundary. (The PAHs and small grains also affect the near-infrared continuum.) The outer radius mainly affects the submillimetre emission. We will see that the model does not well constrain this parameter. The value of R_2 as well and the ratio of the densities in the two components ($A_1/(A_2 R_2^2)$) affect the shape of the spectrum around $50\mu\text{m}$. We use the value of $A_1 = 2 \times 10^4 \text{ cm}^{-3}$ (Pottasch 1984). HRC find $1.56 \times 10^4 \text{ cm}^{-3}$: using this value would slightly change the dust-to-gas ratio but not the derived dust parameters.

Finally, the main constituent of the dust has to be chosen. Because BD +30°3639 is a carbon-rich nebula, only carbon grains are expected to be present: all available oxygen is quickly locked into CO during the mass-loss event, and dust is only formed from the remaining carbon atoms. In recent years attention has shifted from graphites to amorphous grains for the large-grain component of carbon dust (Draine 1989, Sorrell 1989, SK). We find that the mid-infrared emission of BD+30°3639 cannot be fitted as well with large graphite grains, although this might be improved by using a more complicated density distribution. A somewhat better fit in the submillimetre is obtained with the amorphous grains of Preibisch et al. HRC also prefer amorphous grains because of the submillimetre emission. Below we will present fits for both graphite and amorphous grains. For the time evolution calculated in Section 5 we have only used models with amorphous carbon as the

large-grain component. The relative abundances of the different components (large grains, small graphites and two kinds of PAHs) are determined separately in the model. It should be noted that we assume that the dust composition does not depend on position in the nebula. This may be an important simplification.

The band ratios of the PAH features at 3.3, 6.2, 7.7, 8.6 and $11.3\mu\text{m}$ are governed by the size and the hydrogenation of the PAHs. Because the bands at 3.3, 8.6 and $11.3\mu\text{m}$ are due to aromatic C–H modes, whereas the other two are caused by C=C aromatic stretching bands, the hydrogenation will determine the ratio between these lines. The ratio between the 3.3 and $11.3\mu\text{m}$ features is often interpreted as due to the size of the PAHs (Allamandola et al. 1989a, de Muizon et al. 1990), whereas in the SK model the small PAHs emit strongly at $3.3\mu\text{m}$ and the PAH clusters determine the $11.3\mu\text{m}$ feature.

Figure 1 shows the effect of the different dust components on a calculated spectrum. The large grains, due to their low temperature, dominate in the far infrared. The very small grains contribute to both the mid- and near-infrared, the latter because of their very high temperature excursions. The PAHs cause the band features and part of the continuum emission between 6 and $13\mu\text{m}$.

3.5 Determining the fit parameters

In the fitting procedure the distance was kept constant to 2 kpc, which, as mentioned above, should be considered as a lower limit. We then varied the luminosity and the density parameters, while keeping the dust parameters constant, in order to find a parameter set which would approximately reproduce especially the long-wavelength part of the spectrum. After a reasonable fit was obtained, we varied the secondary parameters, such as the relative abundance of each of the dust components, the size distribution of the PAHs and the hydrogen-to-carbon ratio of the PAHs, in order to fit the short-wavelength continuum and the near- and mid-infrared features. Finally, small adjustments were made to all parameters to arrive at the “best fit”.

The resulting fit is shown in Figure 2 using amorphous and Figure 3 using graphite grains. Detailed parameters of the fit are presented in Table 1 for both models. In the upper panel of each Figure the full spectrum is presented. It can be seen that not all observed data points are consistent with each other. Some of the presented data points have been read off from published spectra (Moseley and Silverberg 1985, Allamandola et al. 1989b, Hora et al. 1990, 1993, the IRAS LRS spectrum: IRAS science team 1986, Russel et al. 1977); others come from the compilation by Bentley et al. (1984). The published errors are generally smaller than the size of the symbols, although some points may have larger uncertainties. The J and H data come from the listing of Acker et al. (1992); the original measurements are from Peña and Torres-Peimbert (1987). The K-data are from Hora et al. (1993): the lower data point is the star only, the upper nebula plus star. Data points read off from the spectrum published by Russel et al. are shown by the triangles: at K this spectrum falls below the data from Hora et al. One data point corresponding to the [SIII] emission line at $18.68\mu\text{m}$ is not shown. The IRAS flux densities at 25, 60 and $100\mu\text{m}$ lie above the Kuiper Airborne Observatory measurements. This could be due to aperture effects. The IRAS scale could also be slightly wrong, since it is derived from model fits to the zodiacal emission. New observations at several apertures are desirable to remove this inconsistency. The lower panel shows the new data of Schutte and Tielens (1993).

4 Discussion

4.1 Overview

Figure 2 shows a fit which is accurate over most of the spectrum to within $\leq 20\%$. This is a good result, especially considering that our model is not a perfect representation of the nebula: the incomplete gas–grain interaction (e.g. neglected photoionization), the simple density model and the significant uncertainties in the optical constants of the dust properties. The fit in Figure 3, which uses graphite grains, does not well represent the shape of the continuum around $40\mu\text{m}$. We note that amorphous carbon grains clearly give the better fit, but this is insufficient to decisively choose against large graphite grains. The general expectation that large carbon grains must be amorphous follows more from investigation of the structural chemistry in the ISM (Sorrell 1989) than from our radiative-transfer calculations.

The observations become noisier near $5\mu\text{m}$, which presents a problem in where to define the continuum level. The calculated continuum at these short wavelengths is sensitive to the chosen inner radius, which is constrained by the observed continuum to $(3-5) \times 10^{16}$ cm. The PAH features at 7.7 and $8.6\mu\text{m}$ are not well fitted. For the latter, the SK model consistently predicts values too low by about a factor ≤ 3 and it is likely that the cross section used for this feature is too low. We use the ones published by Léger et al. 1989a (see also d'Hendecourt et al. 1989, de Muizon et al. 1990). The plateau of weaker features between $3.2-3.6\mu\text{m}$ is at present not treated in the SK dust model. The feature at $7.0\mu\text{m}$, which is not fitted, is due to an [ArII] line.

For $\lambda \geq 400\mu\text{m}$ contribution from free-free emission becomes important. The predicted free-free flux, extrapolated from the radio spectrum, is indicated by the dashed line; the solid line includes this contribution.

4.2 The near infrared

The J,H,K fluxes contain a large contribution from free-free and bound-free emission arising from the ionized gas, which is not included in the model. We can calculate this contribution from the known radio flux density, using the tables for a pure hydrogen nebula in Ferland (1980). From this we predict fluxes of 0.13, 0.11 and 0.14 Jy at J,H,K. Added to this should be the contribution from the central star: this can be the dominant source for the coolest planetary-nebulae central stars. For the amorphous-grain model we predict for the star a flux of 0.40, 0.24 and 0.13 Jy at J,H,K. (The higher luminosity required in the graphite-grain model leads to somewhat higher values in that model.) The dotted line indicates the sum of these contributions.

In the amorphous-grain model, we find good agreement at J and H but some emission deficit at K with respect to the data from Russel et al. (1977) and a large deficit with respect to the K-flux from Hora et al. (1993). In the graphite-grain model the K-data from Russel is fitted better, but now the J and H flux is too large indicating that this model requires a too-high stellar luminosity.

The reason for the difference between the Russel et al. data and the Hora et al. data is not clear to us. We note that the flux measured for the central star by Hora et al. is reproduced reasonably well by the model (0.09 Jy measured versus 0.13 Jy predicted). Willner et al. (1972) have also claimed an unexplained excess emission at K.

4.3 Radial profiles and PAH distribution

Figure 4 shows radial cross scans through the nebula at several wavelengths at infinite spatial resolution, as predicted from the final model parameters for the amorphous-grain model. In our model, we find that the radial profile is almost constant with wavelength in the mid-infrared. Only towards the far-infrared and the submillimetre does the nebula become much more extended. The absence of change with wavelength around $10\mu\text{m}$ is in part due to the fact that a significant part of the continuum arises from PAHs, which are also responsible for the broad band features. Figure 5 shows how the radial emission profiles of the different dust components behave separately, at $11.3\mu\text{m}$ and $3.3\mu\text{m}$. The PAHs have a larger extent than either the small graphites or the large grains. At $3.3\mu\text{m}$ the large grains are not plotted because their contribution becomes insignificant.

The profiles of Figure 4 can be compared to published infrared maps (Hora et al. 1990, 1993). The published profiles have different extensions in NS and EW direction: at $10\mu\text{m}$, the-IR profiles in Hora et al. (1993) peak approximately $1.5''$ away from the central position in the NS directions, while in EW direction the peak occurs at about $1.9''$. This immediately shows that a spherically symmetric model has limitations for this nebula. The bottom panel of Figure 4 shows the profile predicted from our model, smoothed to $1.2''$ resolution (where the smoothing was done on a two-dimensional image derived from the profile). The peak now falls at about $1.0''$ from the center, with an uncertainty of about 25%. The model predicts therefore a more compact model than actually observed. The graphite model predicts a somewhat larger inner radius, which in fact would better agree with the observations. However, this is due to the fact that the graphite model requires a higher stellar luminosity, which predicts too high a magnitude for the central star.

Hora et al. (1993) also find that for BD +30°3639 the PAH features are more extended than the $10\mu\text{m}$ continuum, peaking about $0.5''$ further out. This is not seen in our model, and could only be explained if the dust composition changes with radius. In fact, Hora et al. suggest that the difference is due to PAH destruction in the ionized region. The effect is not always seen in young planetary nebulae: Meixner et al. (1993) find that the planetary nebula IRAS21282+5050, which appears to be in a similar evolutionary phase as BD +30°3639, shows the same structure

at several mid-infrared wavelengths. In all these cases is the infrared extent larger than that of the ionized gas.

By comparing our model with observed radial profiles there are two disagreements on a sub-arcsecond scale: i) A too-small inner radius, which may just be a consequence of the simple density distribution chosen, or alternatively it could be improved by assuming a larger distance. ii) A different extent of the observed $11.3\mu\text{m}$ compared to the $10\mu\text{m}$ emission. This points to a potentially more damaging problem and may be caused by our neglect of photo-ionization. First, photo-destruction of PAHs by $\text{Ly}\alpha$ is not treated, and second, the $\text{Ly}\alpha$ gives an additional heating source for the grains in the ionized region. This additional term could slow the decrease in the radial emission profile for all dust components, but especially for the smallest grains. However, the difference in distribution between 11.3 and $10\mu\text{m}$ could only be explained in our model if in the inner regions the PAHs are partly destroyed. From our preliminary inclusion of photo-ionization we found that PAH destruction could not be excluded.

At longer wavelengths the predicted flux distribution becomes more extended. A consequence of the radial extent of the emission is that the observed flux depends on the size of the aperture at the long-wavelength part of the spectrum. We have calculated the observed $450\mu\text{m}$ emission through the $9''$ and $18''$ JCMT apertures, and find 0.15 and 0.28 Jy respectively, compared to the observed values of 0.5 and 0.75 Jy (HRC, after subtraction of the contribution from free-free emission; especially the last value has a large uncertainty). This shows that, although we used the submillimetre flux to constrain the outer radius of the density distribution, in fact the fit here falls short by a factor of three. The flux depends on both the efficiencies and on the temperature of the grains. The temperatures can be calculated in an easy manner; it is very unlikely that they can be wrong by a large factor. The efficiencies are more uncertain, and it is possible that the measured grain properties of Preibisch et al. still underestimate the submillimetre flux. Alternatively, the submillimetre flux could have a contribution from inhomogeneous grain conglomerates, the so-called “fluffy grains” (Wright 1987, Krügel & Siebenmorgen 1994). These grains have higher emissivity by large factors in the submillimetre regime.

4.4 PAH size distribution and hydrogenation

In the model, the PAH emission is dominated by the largest PAH component, the PAH clusters. The contribution from the small PAHs is almost negligible. This agrees with Hora et al. (1993), who conclude from a comparison of their $11.2\mu\text{m}$ image with a $3.28\mu\text{m}$ image by Roche (1989) that the same component appears to be responsible for both features. In order to explain the line ratios, a very low hydrogenation is needed for the clusters.

In AGB and post-AGB objects, the $11.3\mu\text{m}$ is often due to SiC emission. This raises the question whether in BD +30°3639 it also contributes to the observed feature. Observationally, it is expected that SiC emission will peak close to the star where PAHs are probably destroyed. Therefore the data from Hora et al. would favour PAHs as the origin of the $11.3\mu\text{m}$ emission in BD +30°3639, although it is possible that sub-arcsecond imaging would reveal a SiC component. It seems likely that SiC is only a minor contributor to the $11.3\mu\text{m}$ (but this could well be different in other planetary nebulae). We note that identifying the $11.3\mu\text{m}$ feature with SiC (e.g. HRC) would result in an even lower hydrogenation of the PAHs but also allow for a larger contribution of small PAHs. In such models the low hydrogenation also applies to the small PAHs

4.5 Internal extinction

In spite of the low extinction towards BD +30°3639, we predict a significant extinction towards the central star, caused by the dust inside the nebula. We find $A_V = 0.43$ for the amorphous-grain model, and approximately the same for the graphite model. The extinction towards planetary nebulae is normally derived from the ratio of the hydrogen lines. However, the assumption that the extinction towards the star and the nebula are equal may not be valid for high-density nebulae such as BD +30°3639. This will affect the commonly used Zanstra method to determine central-star temperatures, which uses the ratio of the visual stellar flux over the $\text{H}\beta$ flux from the nebula. In the case of extinction internal to the nebula, the $\text{H}\beta$ flux will be less affected than the stellar flux. For BD +30°3639, the effect could lower the stellar temperature from the Zanstra value of $30\,000$ K (used in this paper) to $28\,000$ K.

The extinction of BD+30°3639 has also been measured from the depth of the 2200\AA absorption feature towards the central star. This feature is probably caused by small graphites in the interstellar

medium. However, the dust properties in circumstellar mediums are different and the internal extinction in the nebulae would not necessarily cause such a feature. Significant internal extinction can therefore not be ruled out on the basis of presently available observations. Köppen (1977) suggested that internal extinction should be important for a small number of planetary nebulae, and derived that especially for BD +30°3639 the observed extinction should be almost exclusively caused by the nebula.

4.6 Total dust mass and dust-to-gas ratio

Adding up all the dust components listed in Table 1, we arrive at a dust-to-gas mass ratio of 3.5×10^{-3} for amorphous grains (and somewhat larger if graphite grains are assumed). This is smaller than the ratio found in the ISM (7×10^{-3} to 10^{-2}). It should be noted that our value only applies to the ionised region, since the gas density in the neutral region is not known. Smaller ratios are commonly found in PN (e.g., HRC, Barlow 1993) and gives problems if we assume that the dust in the ISM comes from PN. It is possible that the ratio in the ionised region is lowered by two competing processes: dust destruction by UV photons, and dust removal to the outer neutral region through radiation pressure. In both cases it is expected that the dust-to-gas ratio will be higher in the neutral region.

The total predicted gas mass is $2.5 M_{\odot}$. This value is rather uncertain: it assumes that the dust-to-gas ratio is constant throughout the nebula, and it depends on the outer radius which is not well constrained by our model. However, the large value clearly favours a high-mass progenitor which was able to shed at least a solar mass from its atmosphere before leaving the AGB.

4.7 The evolutionary status of BD +30°3639

The model predicts a stellar luminosity of $1.3 \times 10^4 L_{\odot}$, which is consistent with the lower limit found from the radio emission. As before, we stress that we used a low value for the distance, and that the actual luminosity may be even higher. The luminosity is high for a PN. The luminosity–core mass relation (e.g. Boothroyd and Sackman 1988, Pottasch 1992) implies a corresponding core mass of $0.7\text{--}0.75 M_{\odot}$. Most PN have core masses around $0.6 M_{\odot}$, corresponding to luminosities of approximately $6 \times 10^3 L_{\odot}$. Of the well-known galactic PN, only NGC 7027 and NGC 6369 are known to have such high luminosities (Gathier and Pottasch 1989), where it should be noted that NGC 7027 appears to have entered the cooling track in the HR diagram, and therefore will have had a higher luminosity in the past. The high core mass of BD +30°3639 implies a massive progenitor of several solar masses.

The total nebular mass in our fit of about $2.5 M_{\odot}$, although poorly determined, also implies a massive progenitor of several solar masses, which has shed a large amount of mass. The density of the r^{-2} component, together with the known expansion velocity of 22 km s^{-1} (Acker et al. 1992), yields a mass-loss rate at the AGB of $2 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$. This is an extremely high rate, with most observed mass-loss rates on the AGB in the range $2 \times 10^{-5}\text{--}10^{-7} M_{\odot} \text{ yr}^{-1}$. It seems likely that the most massive objects experience the highest mass-loss rates, which would make the calculated value for BD+30°3639 acceptable.

From the inner radius of the nebula, and using the known expansion velocity, we derive an age of the nebula of around 600 yr, measured from the end of the mass-loss phase. Schönberner (1989) finds that for stars with high core mass, the transition time between AGB and early PN is 500–1000 yr. Therefore, the model results are self-consistent if BD +30°3639 is far more massive than most galactic PN. Both the evolutionary time scale and the low temperature of the central star put it in an early phase of a PN evolution.

5 The infrared evolution of BD+30°3639

The density distribution used in the final fit allows one to calculate the preceding infrared evolution of BD +30°3639. This is particularly interesting because stellar evolution at the phase immediately before appearance of the visible PN is not well understood. The main observational reasons are first the high circumstellar extinction, rendering many objects invisible at optical wavelengths, and second the fact that for those stars which are optically visible, distance determinations have not yet been possible. Surveys have been carried out using the IRAS database, since most of the stellar energy is converted to circumstellar infrared emission (Volk and Kwok 1989). The surveys have been

partly successful: a number of objects have been found, but their precise evolutionary phase could not easily be determined (e.g. Trams et al. 1991).

In calculating the progenitor evolution we have made a number of simplifying assumptions. First, the entire nebula was represented only by the $1/r^2$ dust density component. We extended the wind-like component of the fit in Section 3 inward, keeping the total nebular mass constant. This is equivalent to assuming that the circumstellar envelope of BD +30°3639 was formed during a single phase of constant mass loss. Second, we calculated the age of BD +30°3639 from the adjusted inner radius and the observed expansion velocity of 22 km s^{-1} . Third, we assumed that the mass loss terminated at a stellar temperature of 5000 K, and that the stellar temperature has increased linearly during the post-AGB evolution. The last assumption is in principle only valid for low and intermediate core masses. For core masses larger than $0.6 M_{\odot}$, the temperature increase becomes faster after $t = 500 \text{ yr}$, corresponding to $T_* = 10^4 \text{ K}$ (Schönberner, 1989). Therefore, we will somewhat overestimate the temperature increase in the first 500 yr.

The first step of the evolutionary sequence is calculated when the inner radius reaches 10^{15} cm , approximately ten years after the mass loss ends. In this way we avoid the problem at what distance from the star the dust particles form, which is a major uncertainty in modeling on-going mass loss, but not the subject of the present paper.

Figure 6 shows six evolutionary steps. The corresponding parameter values are listed in Table 2. The first step shows a steep cut-off around $2.5 \mu\text{m}$, caused by the high optical depth in the circumstellar envelope. At this phase the visual extinction will drop quickly, and the star will become visible at near-infrared wavelengths within 25 yr. Optical visibility follows after $\sim 100 \text{ yr}$. The peak flux of the dust emission is seen to shift to longer wavelengths in subsequent time steps, with the far-infrared continuum slowly rising during the evolution. The latter effect is caused by the fact that the dust temperature in the outer regions of the cloud increases as the optical depth towards the star decreases, giving a stronger radiation field in the outer layers.

The development of the PAH features is shown in Figure 7a. They develop quickly when the star is still relatively cool, and reach full strength when the star is about 15000 K. At this time the star is still too cool to significantly ionize the nebula: the PAH features develop before a planetary nebula becomes visible. Interestingly, the flux at $3.3 \mu\text{m}$ stays almost constant: the drop in continuum flux is compensated by the increasing band emission. At later stages (not shown) the line intensity will go down as the dust moves away from the star.

In Figure 7b cross scans through the nebula at several wavelengths are shown. The submillimetre emission is more extended, especially at later phases. The distribution implies that aperture effects at these measurements are much less severe for AGB or very young post-AGB objects, a prediction that can be easily tested.

From sequence 3 onwards ($t = 360 \text{ yr}$), the J,H,K colours are dominated by the central star, and therefore resemble progressively hotter black bodies. In contrast, in the L-band dust emission is present at most stages of evolution, and the object will show an L-excess in the H–K, K–L diagram as compared to the black-body line. Only in the first $\sim 100 \text{ yr}$ are the J,H,K colours influenced by the dust: in this phase the optical depth at $1\text{--}2 \mu\text{m}$ is still high. This implies that the J–H, H–K diagram shows an excess over the black-body line only for objects which have very recently experienced mass loss or are still in the mass-loss phase. For more evolved objects the diagram will show stellar colours only. We conclude that the near-infrared colours are not a very sensitive tracer when the stellar temperatures approach the planetary-nebula phase.

Table 2 lists the IRAS flux densities during the evolution, obtained by convolving the calculated spectra with the IRAS transmission functions. The IRAS colours approximate a black body with an equivalent temperature of 350 K in the first model, and evolve towards the planetary nebula regime. Figure 8 presents the evolution of the IRAS colours in the post-mass-loss phase. Here the colours evolve significantly during the first 500 yr, after which the evolution slows down. For comparison the figure also shows the colours of all Galactic planetary nebulae with good, three-band IRAS detections. At the stage that the colour evolution slows down, the colours are already close to those exhibited by planetary nebulae. Thus, in order to find the further evolved “transition” objects, surveys should include objects with infrared IRAS colours close to those of PN. Most surveys, however, have concentrated on objects with colours more similar to AGB stars (e.g., van der Veen, 1988). Such surveys will have been biased in favor of young post-AGB objects, or to objects with slower evolving dust shells, such as found in binary systems. In order to find all objects in transition towards planetary nebula, a large range of IRAS colours is needed.

6 Summary

We have used a radiative transfer code for transiently heated dust particles. Our model include PAH molecules to fit the full IR spectrum of the planetary nebula BD +30°3639. A good fit to the spectral energy distribution is obtained when we use amorphous carbon grains for the large particles. The model does not reproduce the observed difference between the radial profile at $10\mu\text{m}$ and $11.3\mu\text{m}$. This is probably due to the fact that we do not treat photo-ionization and therefore do not include a $\text{Ly}\alpha$ heating term. The model implies that the observed difference can only be explained if PAHs are partly destroyed in the inner (ionized) region; this PAH destruction could also be due to $\text{Ly}\alpha$ photons. In the submillimetre, the predicted flux is lower than observed in the JCMT aperture. This could possibly be explained by a component of of large, inhomogeneous (“fluffy”) dust particles, which have an enhanced submillimetre emissivity compared to their pure spherical counter parts.

The result are consistent with a classification of BD +30°3639 as a high-mass planetary nebula, with a core mass of $\sim 0.7 M_{\odot}$, and a mass-loss rate on the AGB of $2 \times 10^{-4} M_{\odot} \text{yr}^{-1}$. The PAH band ratios imply that the PAH are mainly in the form of clusters, which are strongly de-hydrogenated. Compared to the PAH abundance the contribution of SiC grains to the $11.3\mu\text{m}$ feature is probably small. We find that the dust-to-gas mass ratio in the ionised region is somewhat smaller than in the ISM, in agreement with earlier studies (e.g. Hoare et al. 1992).

We have calculated the infrared spectrum of BD +30°3639 at several stages of its post-AGB evolution. We find that the IRAS colours of evolved high-mass post-AGB objects($t > 500\text{yr}$) should resemble those of planetary nebulae. Many surveys of post-AGB have concentrated on objects with IRAS colours intermediate between AGB stars and planetary nebulae, and may thus have been missed older post-AGB objects. Of the near-infrared bands, J,H and K mainly measure the central star; only the L-band contains significant dust emission at nearly all evolutionary stages.

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Figure Captions

- Figure 1: Contribution of the different dust components to the calculated spectrum. The dashed line represent the model with large amorphous carbon grains only. The contribution from large grains and small graphites is given by the dotted line and, the model including PAHs is shown by the full line.
- Figure 2: a) The spectral energy distribution of BD +30°3639. Observations are shown by squares, the model with amorphous carbon grains for the large-grain component is depicted by a solid line. the triangles present data from Russel et al. (1977). In the submillimetre the contribution of free-free emission (separately indicated by the dashed line) has been added. The dashed line in the near infrared includes the contribution from bound-free and free-free emission to the J,H,K,L. The lowest K-point is a measurement of the star only. b) High-resolution spectrum of BD +30°3639 between 3 and 14 μ m. Observations shown as small circles are from Schutte et al. (1993) and the full line is the model fit.
- Figure 3: As Figure 2, but now the fit is derived with Draine & Lee optical constants for the large-grain component.
- Figure 4: a) The normalized radial surface-brightness distribution across the nebula at several wavelengths, for the amorphous-grain model. The top axis shows the radius in arcseconds. b) The 10 μ m model profile smoothed to 1.2'' resolution, as in a). Smoothing was done with a Gaussian on a two-dimensional image derived from the model profile.
- Figure 5: The distribution of the individual dust components for the radial profiles at 3.3 μ m (upper panel) and 11.3 μ m (lower panel). The large grains are not shown for the 3.3 μ m because they do not give a significant contribution.
- Figure 6: The infrared time evolution between 0.1 and 1000 μ m of BD +30°3639. The first evolutionary sequence is calculated 13 years after the mass loss ends. The contribution from radio emission is not included.
- Figure 7: a) The evolution of the PAH bands between 13 and 900 years after the mass loss ends. b) The radial surface-brightness distribution across the nebula at the time steps of Figure 6.
- Figure 8: The calculated evolution of the IRAS colours for the time steps of Figure 6. The circles show the actual colours of the Galactic planetary nebulae with good three-band detections where the position of the IRAS source and the planetary nebula agree within 15''.

Table 1: Model parameters of BD +30°3639

Model	I (amorphous)	II (graphite)	I (amorphous)	II (graphite)
<i>Dust parameters</i>			<i>Nebular parameters</i>	
M_d/M_g	3.5×10^{-3}	9.2×10^{-3}	D (kpc)	2
<i>Large carbon grains</i>			T_* (K)	3×10^4
Lower size (Å)	300	300	L_* (L_\odot)	1.3×10^4
Upper size (Å)	1200	1200	A_1	2×10^4
Abundance	8.4×10^{-5}	2.4×10^{-4}	A_2	2.3×10^{38}
<i>Small graphites</i>			R_i (cm)	4×10^{16}
Lower size (Å)	10	10	R_o (cm)	2.5×10^{18}
Upper size (Å)	80	80	R_2 (cm)	8×10^{16}
Abundance	2×10^{-5}	6×10^{-5}		
<i>Small PAH</i>				
Number of C-atoms	25	25		
Abundance	7×10^{-8}	10^{-8}		
H/C atom ratio	0.2	0.1		
<i>PAH clusters</i>				
Number of C-atoms	250	250		
Abundance	5×10^{-6}	10^{-6}		
H/C atom ratio	0.04	0.2		
visual extinction A_V	0.43	0.45		

M_d/M_g is derived from the calculated dust density by assuming an electron density of $2 \times 10^4 \text{ cm}^{-3}$. The abundance of the various dust components is defined as the number of C-atoms locked up in dust relative to the number of H-atoms, and is calculated using the same electron density

Table 2: The post-AGB evolution of the progenitor of BD +3030°3639

T_* (K)	R_i (10^{16} cm)	t (yr)	A_V	F_{12}	F_{25}	F_{60}	F_{100}	F_{450}
						(Jy)		
5000	0.1	13	29.6	225	165	52	18	0.24
10000	1.3	180	2.3	217	262	104	37	0.38
15000	2.6	360	1.1	161	284	141	51	0.47
20000	3.9	540	0.74	124	270	157	57	0.51
25000	5.2	720	0.55	100	249	163	61	0.53
30000	6.5	900	0.43	78	225	164	62	0.55

The flux densities at 12–100 μm are derived by convolving with the IRAS bandpasses. the 450 μm is a narrow-band flux, but not corrected for aperture effects such as would be measured at JCMT. In the last few models the actual observed 450 μm flux would be higher due to free-free emission from the ionized gas. The time is calculated assuming a constant expansion velocity of 22 km s^{-1} .